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13. ABSTRACT (Maximum 200 words)

The aim of the funded research has been to investigate the use of feedback in phase-coherent electronic systems. Quantum dots afford the most controllable quantum system presently being investigated, because dc voltages applied to gates control the confining potentials that form the system. Over the course of the funding cycle, discoveries were made concerning the sensitivity of quantum dots to external perturbation, universal theoretical laws for quantum chaotic systems, and the crossover from open to closed quantum systems, the relation between ground and excited states, and the sensitivity of phase coherence to external radiation. Overall, **10 Physical Review Letters**, **2 Science Papers**, and **1 Applied Physics Letter** were among the papers published that were supported by this grant.

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(3) List of Figures

(4) Statement of the Problem Studied

Progress was made in understanding the applicability of universal theoretical laws based on random matrix theory, that describe the sensitivity of quantum systems to external perturbation, to real semiconductor devices. A clear understanding of this is crucial to understanding how feedback can be applied to such quantum systems. The quantum system we investigated was the ballistic, gate-defined quantum dot, notable for its easy experimental control.

(5) Summary of most important results

Two papers in particular directly addressed the goal of the proposal: "Feedback Control of a Quantum Dot" and "High Bias Transport and Magnetometer Design in Open Quantum Dots." The "High bias.." paper in particular characterized (as a function of temperature, bias current and device size) how sensitive a detector a quantum dot is, and compared these numbers to alternative state-of-the-art technologies such as SQUIDs and Hall probes. The paper also emphasizes that unlike these other technologies, the quantum dot intrinsically functions as an *absolute* magnetometer — sensitive to the absolute value of B — rather than a relative magnetometer (sensitive to changes in B). The paper "Feedback Control." besides providing a review of the experimental situation in quantum dots, also stated an important new theoretical result concerning how many control parameters are needed to provide generic feedback control of conductance. The answer, based on an analysis known in continuum percolation theory, is that two controls are sufficient.

The other papers, including six PRLs published in 1998, focused on problems of decoherence in open quantum dots, and on the universality of the statistics of Coulomb blockade peaks in interacting electronic systems.

In terms of applicability to the goals of the proposal, the most important work of the year concerns dephasing in quantum dots. Many words have been written explaining how low temperatures can be swapped for small size, and as nanotechnology evolves, devices will move out of the cryostat without losing their essential quantum features by becoming small. But the fact is, no one knows what this scaling between temperature and size is, since the fatal effect of temperature is decoherence. The papers by A. Huibers ,which were followed up with another PRL in 1999, go a long way toward establishing this scaling relation, at least in the low temperature regime.

A study of advective transport in a random-magnetic-field system, somewhat unrelated to the goals of the proposal, were supported by this grant as well. Advection is flow along streamlines, like smoke rising from a cigarette. This is not how electrons flow in usual (electrostatically) disordered systems, but it is what happens in magnetically disordered systems. The motivation for this work is the known large magnetoresistances in these systems. We developed a novel experimental approach (previous work, Mancoff, et al.) using the attachment of high-field magnets directly to the surface of a clean 2D electron gas. With this technique we were able to test many theoretical predictions for advective flow of charge in 2D. It is worth noting that the first author of this paper was an undergraduate, now studying for his Ph.D. in Physics at Harvard.

(6) List of Manuscripts published under ARO sponsorship:

Science

D. R. Stewart, D. Sprinzak, C. M. Marcus, C. I. Durüoz, J. S. Harris, "Correlation Between Ground and Excited State Spectra of a Quantum Dot" Science 278, 1784 (1997).

M. Switkes, C. M. Marcus, K. Campman, and A. C. Gossard, "An Adiabatic Quantum Electron Pump" Science 283, 1905 (1999).

Physical Review Letters

J. A. Folk, S. R. Patel, S. F. Godijn, A. G. Huibers, S. M. Cronenwett, C. M. Marcus, K. Campman, and A. C. Gossard, "Statistics and Parametric Correlations of Coulomb Blockade Peak Fluctuations in Quantum Dots" Phys. Rev. Lett. **76**, 1699 (1996).

I. H. Chan, R. M. Clarke, C. M. Marcus, K. Campman, and A. C. Gossard, "Ballistic Conductance Fluctuations in Shape Space" Phys Rev. Lett. 74, 3876, (1995).

A. G. Huibers, M. Switkes, C. M. Marcus, K. Campman, A. C. Gossard, "Dephasing in Open Quantum Dots" Phys. Rev. Lett. **81**, 200 (1998).

S. M. Cronenwett, S. R. Patel, C. M. Marcus, K. Campman, and A. C. Gossard, "Mesoscopic Fluctuations of Elastic Cotunneling in Coulomb Blockaded Quantum Dots" Phys. Rev. Lett. **78**, 2312, (1997).

S. R. Patel, S. M. Cronenwett, D. R. Stewart, A. G. Huibers, C. M. Marcus, C. I. Durüoz, J. S. Harris, K. Campman, A. C. Gossard, "Statistics of Coulomb Blockade Peak Spacings" Phys. Rev. Lett. **80**, 4522 (1998).

A. G. Huibers, C. M. Marcus, P. W. Brouwer, C. I. Durüoz, J. S. Harris Jr., "Distributions of the Conductance and its Parametric Derivatives in Quantum Dots" Phys. Rev. Lett. **81**, 1917 (1998).

S. M. Cronenwett, S. M. Maurer, C. M. Marcus, C. I. Duruöz, and J. S. Harris, Jr. "Mesoscopic Coulomb Blockade in One-Channel Quantum Dots" Phys. Rev. Lett. **81**, 5904 (1998).

S. R. Patel, D. R. Stewart, C. M. Marcus, M. Gökçedag, Y. Alhassid, A. D. Stone, C. I. Duruöz, and J. S. Harris, Jr., "Changing the Electronic Spectrum of a Quantum Dot by Adding Electrons" Phys. Rev. Lett. **81**, 5900 (1998).

S. M. Maurer, S. R. Patel, C. M. Marcus, C. I. Duruöz, J. S. Harris, Jr., "Coulomb Blockade Fluctuations in Strongly Coupled Quantum Dots", Phys. Rev. Lett. **83**, 1403 (1999).

A. G. Huibers, J. A. Folk, S. R. Patel, C. M. Marcus, C. I. Duruöz and J. S. Harris, Jr., "Low-Temperature Saturation of the Dephasing Time and Effects of Microwave Radiation on Open Quantum Dots", Phys. Rev. Lett. **83**, 5090 (1999).

Applied Physics Letters

M. Switkes, A. G. Huibers, C. M. Marcus, K. Campman, A. C. Gossard " High Bias Transport and Magnetometer Design in Open Quantum Dots" Appl. Phys. Lett. **72**, 471 (1998).

Others

F. B. Mancoff, L. J. Zielinski, C. M. Marcus, K. Campman, and A. C. Gossard, "Shubnikov-de Haas Oscillations in a Two-Dimensional Electron Gas in a Spatially Random Magnetic Field", Phys. Rev. B (RC) **53**, 7599 (1996).

L. Zielinski, K. Chaltikian, K. Birnbaum, C. M. Marcus, K. Campman, and A. C. Gossard, "Classical Advection of Guiding Centers in a Random Magnetic Field", Europhys. Lett. **42**, 73 (1998).

C. M. Marcus, S. R. Patel, A. G. Huibers, S. M. Cronenwett, M. Switkes, I. H. Chan, R. M. Clarke, J. A. Folk, S. F. Godijn, K. Campman and A. C. Gossard, "Quantum Chaos in Open versus Closed Quantum Dots: Signatures of Interacting Particles", Chaos, Solitons and Fractals 8, 1261 (1997).

A. G. Huibers, M. Switkes, C. M. Marcus, K. Campman, A. C. Gossard, "Dephasing in Open Quantum Dots" Physica B **249-251**, 348 (1998).

C. M. Marcus "Feedback Control of a Quantum Dot" Proceedings of the 4th Experimental Chaos Conference, Boca Raton, FL (World Scientific, Singapore, 1998).

(7) Scientific Personnel:

Andrew Huibers, completed Ph.D., founded start-up company making MEMs-based microminiature display chips. Hired two others in group, Sam Patel, and Randall True.

Fred Mancoff won the APS Apker Award, a single-winner national award for undergraduate research.

Randall True, undergraduate research student (supported by AASERT grant). Graduated with Honors, received the Rebecca L Carrington Award.

Sara Cronenwett, graduate student, visited Delft Institute of Technology for 6 month research exchange program, resulting in a first author paper in the journal *Science*.

Kevin Birnbaum, undergraduate research student. Graduated with Honors. Presently a graduate student at CalTech (with Jeff Kimball).

(8) Report of Inventions:

None that resulted from ARO-sponsored research.

(9) Bibliography

(10) Technology Transfer

Two graduate students (Huibers and Patel) and an undergraduate (True), all of whom were at some point supported by this grant, began a "Silicon Valley Start-up" in 1998, supported by venture capital funding. The founder and CTO of the company is Andrew Huibers (see papers above). The product is not directly connected to the research described above, but does involve microfabrication, electron beam lithography, deposition, all techniques that were used and developed by these three during their time working in our group. In fact, the company, called Reflectivity Inc., still occasionally borrows lab equipment. The product that Reflectivity Inc. is focussing on is microminiature display technology, an anticipated multi-billion dollar industry with application ranging from personal video displays to projective displays in digital movie theaters.